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COARSE-TO-REFINED ROAD ALIGNMENT EXTRACTION AND PARAMETERIZATION FROM MLS POINT CLOUDS

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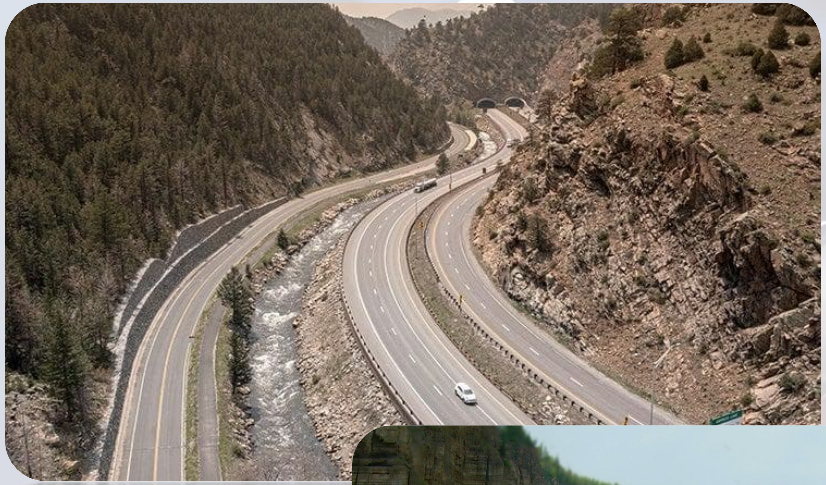
PRESENTATION OVERVIEW

- Why Road Alignment Data Matters
- Our Coarse-to-Refined Framework
- Road Geometry Extraction
- Alignment Identification & Parameterization
- Results & Validation
- Conclusions & Future Work

WHY ROAD ALIGNMENT MATTERS

- > 25% of US roadway deaths occur on curves (FHWA)
- Sharp curves & long tangents: visibility↓, driver strain↑
- Road geometry data essential for safety audits, BIM, simulation
- Current reality: design records missing, outdated, or inaccurate
- Manual surveys: slow, labor-intensive, require lane closures



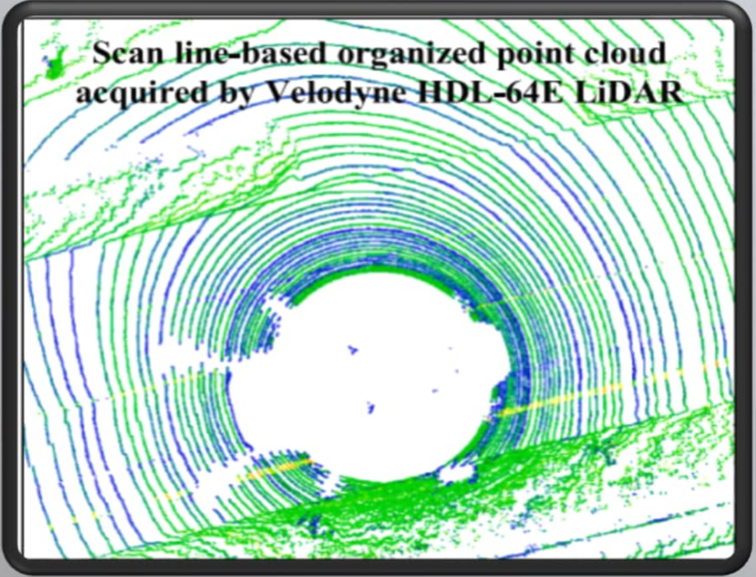
I-70 Glenwood Canyon

Mobile Laser Scanning (MLS) offers a faster, safer alternative

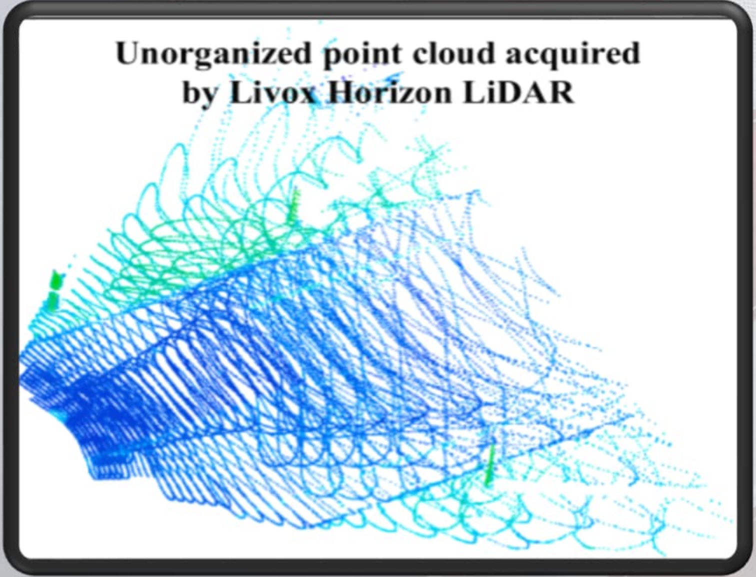
THE DATA CHALLENGE

- Traditional MLS systems: expensive scan-line LiDAR
- Solid-state LiDAR: affordable — but produces unordered point clouds
- Unordered points: traditional methods fail (designed for scan-line data)
- Existing alignment methods: limited to simple geometry (lines + arcs only)

SCAN-LINE BASED



UNORGANIZED POINT CLOUD

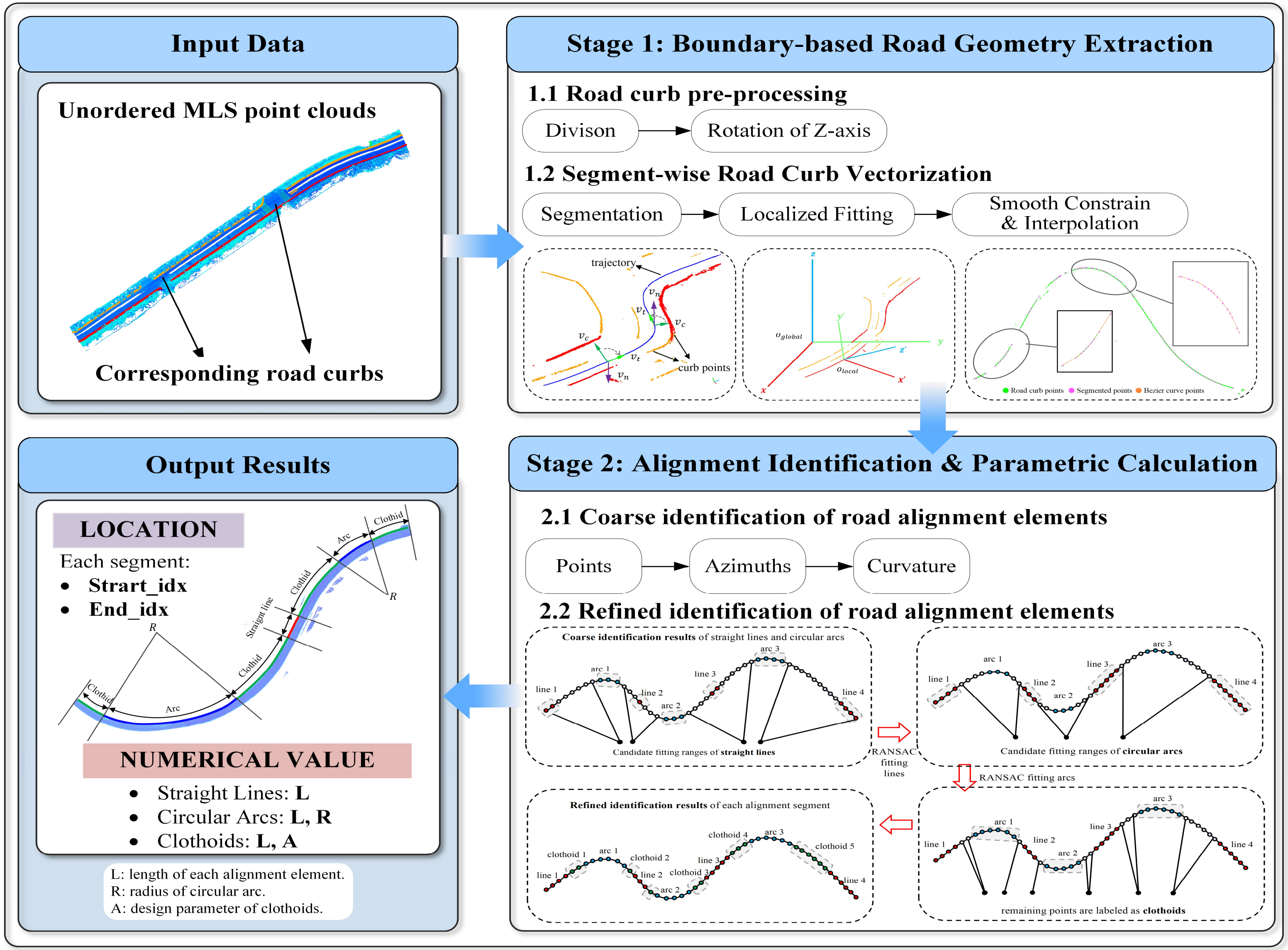


OUR COAESE-TO-REFINED FRAMEWORK

MLS POINT CLOUD → ROAD GEOMETRY EXTRACTION → ALIGNMENT IDENTIFICATION → PARAMETERS

TWO-STAGE APPROACH: COARSE ESTIMATION GUIDES REFINED MODEL FITTING

HANDLES ALL STANDARD ELEMENTS: LINES, CIRCULAR ARCS, CLOTHOIDS



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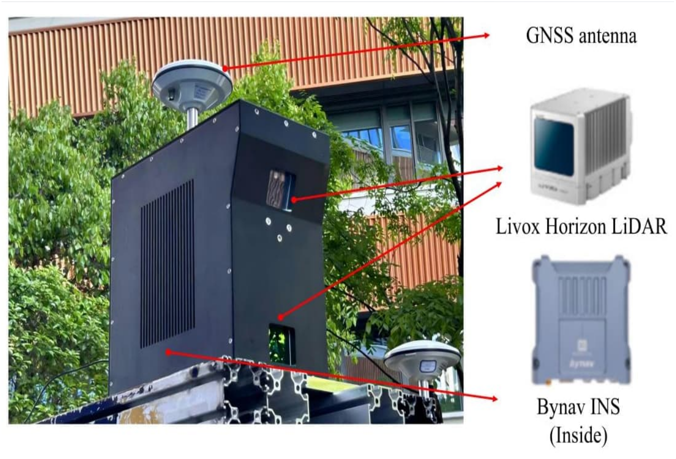
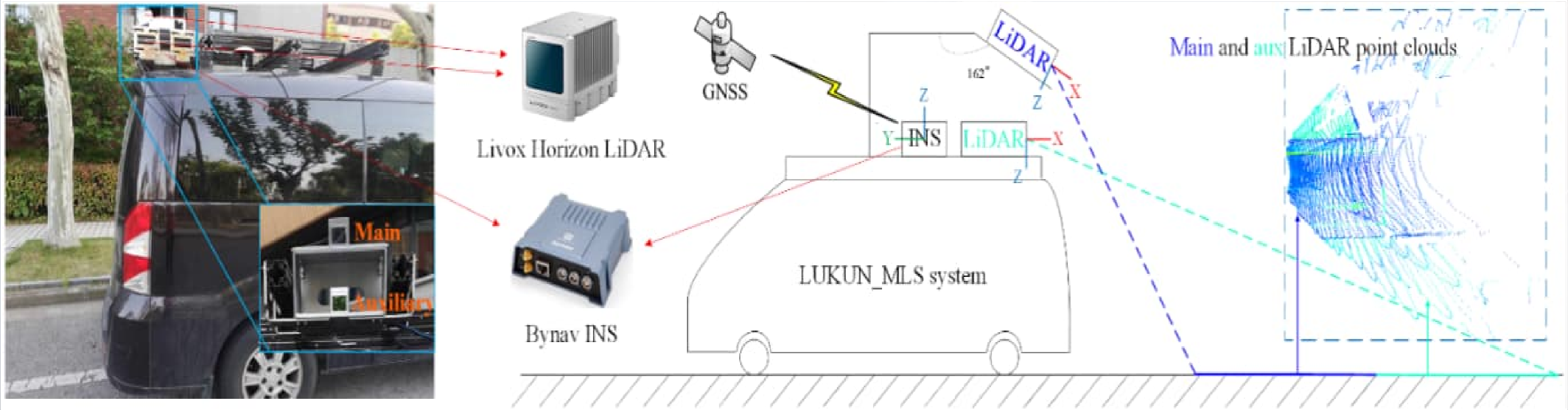
PROPOSED LIGHTWEIGHT MLS SYSTEM





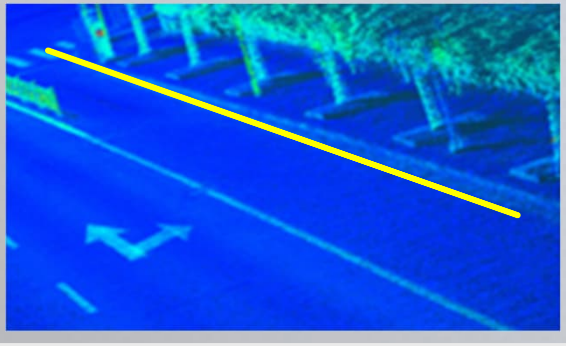
- Self-developed system: 2 LiDARs + 1 INS unit
- Main LiDAR: high-density pavement and curb scanning
- Auxiliary LiDAR: surrounding road context
- INS: precise position and orientation for georeferencing

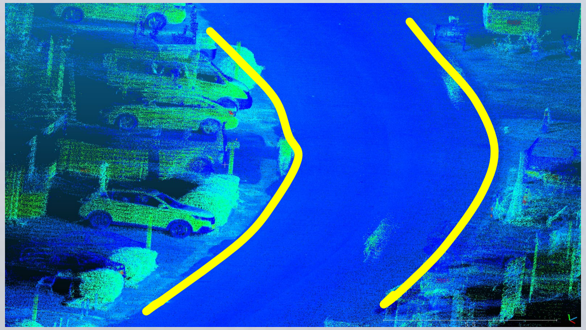
Solid-state LiDAR: uniform coverage without scan-line assumption

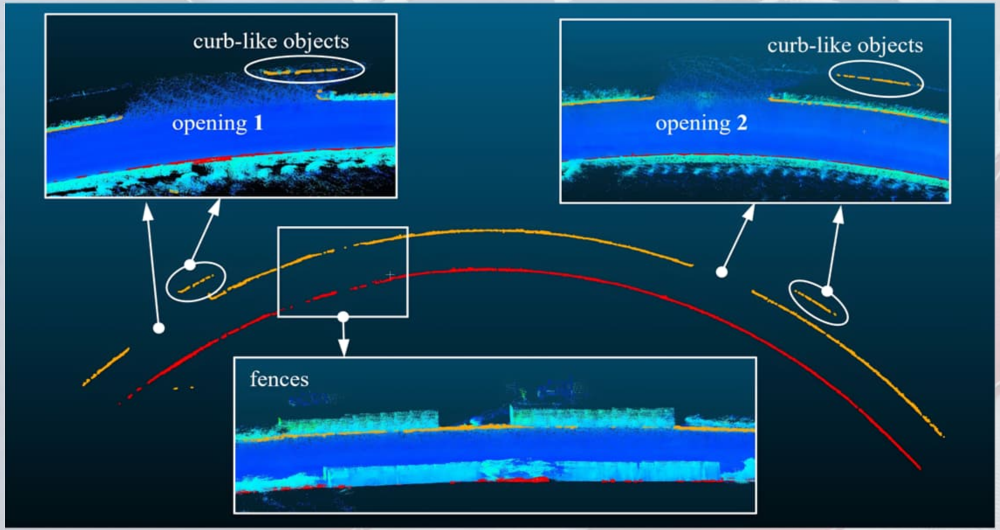
STEP1: ROAD GEOMETRY EXTRACTION

1.1 ROAD CURB PRE-PROCESSING

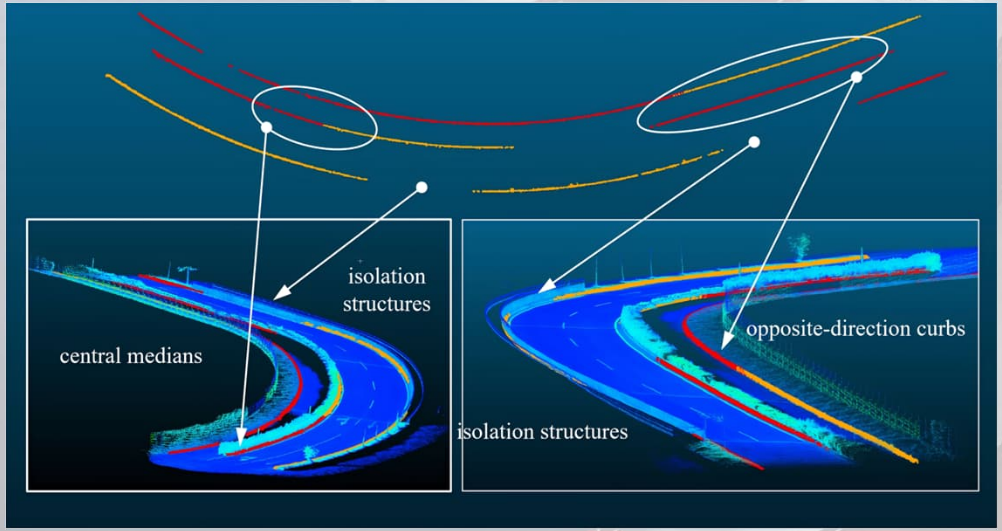
ROAD BOUNDARIES







- CURB-LESS SCENARIOS: CONTOUR-BASED BOUNDARIES
- UNORDERED POINT CLOUDS WITH SIMILAR GEOMETRIC PATTERNS
- ROBUST CURB EXTRACTION THROUGH DATA FUSION AND REGISTRATION [1, 2]
- PRE-SEGMENTED CURB POINT CLOUDS, BUT OCCASIONAL ERRORS:
  - INCOMPLETENESS AND NOISE
  - CURB MISASSOCIATION

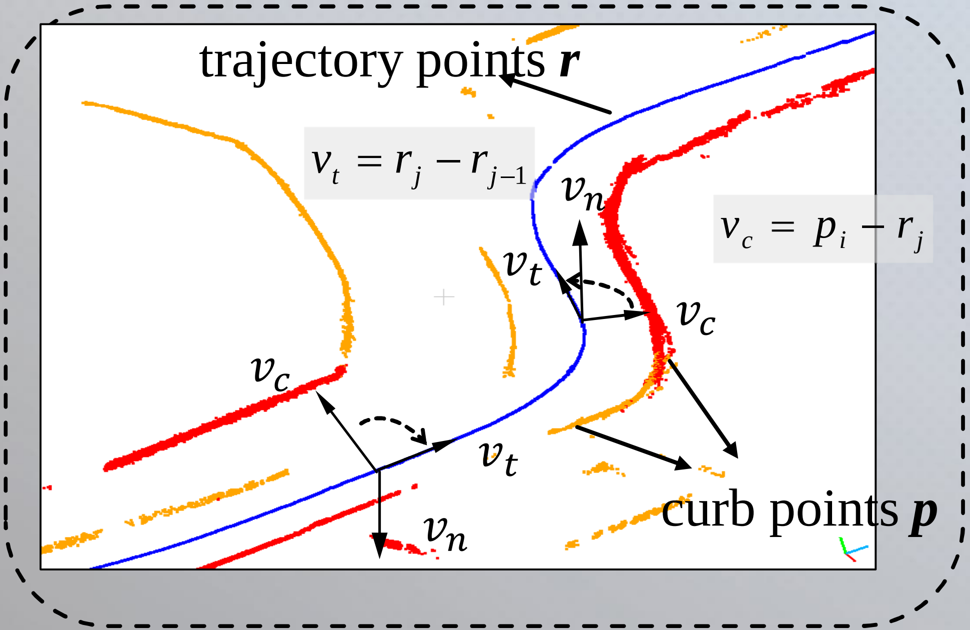


1. Zou, Z., H. Lang*, J. Lu, and Q. Ma. Coarse-to-refined road curb segmentation from MLS point clouds. *Automation in Construction*, 2024, Vol. 166, p.105586.
2. Zou, Z., H. Lang*, Y. Lou, and J. Lu. Plane-based global registration for pavement 3D reconstruction using hybrid solid-state LiDAR point cloud. *Automation in Construction*, 2023, Vol. 152, p.104907.

STEP1: ROAD GEOMETRY EXTRACTION

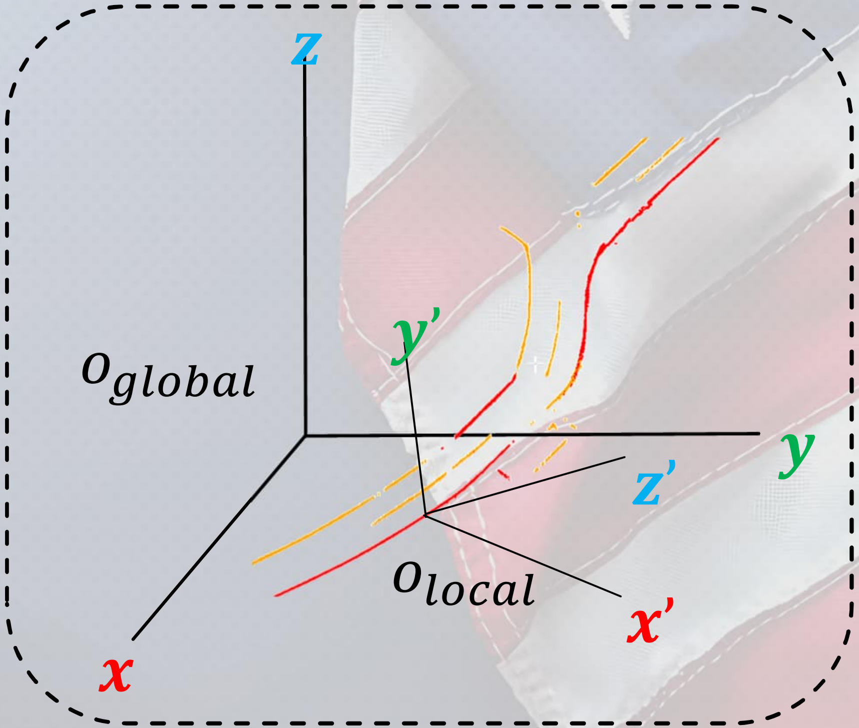
1.1 ROAD CURB PRE-PROCESSING

a. DIVISION & SELECTION OF CURBS



- N_Z OF CROSS PRODUCT INDICATES THE CURB SIDE: $N_Z > 0$, RIGHT; $N_Z < 0$, LEFT
- SELECT ONE SIDE:
  - MORE CONTINUOUS & COMPLETE COVERAGE

b. ROTATION OF Z-AXIS



- ALIGNS THE Z-AXIS WITH THE PAVEMENT NORMAL
- NOT CHANGE THE 3D SHAPE OF THE CURB

STEP1: ROAD GEOMETRY EXTRACTION

1.2 AFTER PRE-PROCESSING, THE CURB POINT CLOUD REMAINS DISCRETE, UNORDERED, AND CLUTTERED WITH NOISE AND GAPS

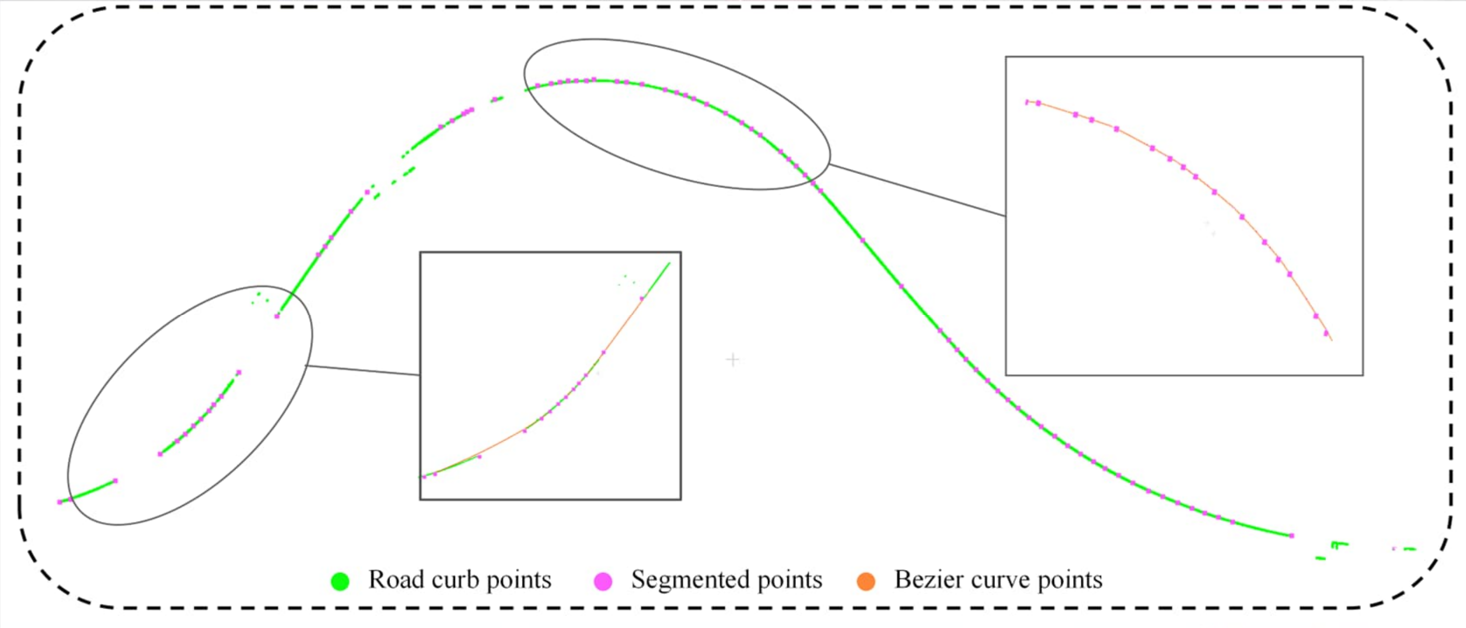
a. SEGMENTATION → Spatially Reordered → Douglas–Peucker

b. LOCALIZED FITTING → Each segment fitting with cubic Bézier curves

c. SMOOTHING CONSTRAINTS & INTERPOLATION

- ✓ REDUCES DATA VOLUME
- ✓ SUPPRESSES LOCAL NOISE
- ✓ IMPROVES GEOMETRIC QUALITY

- A LIGHTWEIGHT LOCAL OPTIMIZATION:
  - ADJUSTS ONLY SHARED ENDPOINTS TO ENFORCE C_1 AND C_2 CONTINUITY
- OPTIMAL REPLACEMENTS:
  - SEARCH AREA → POINTS WITHIN A 0.5 M RADIUS
  - SEARCH TARGET → MINIMIZE THE LOSS FUNCTION



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STEP2: COARSE ALIGNMENT ID.

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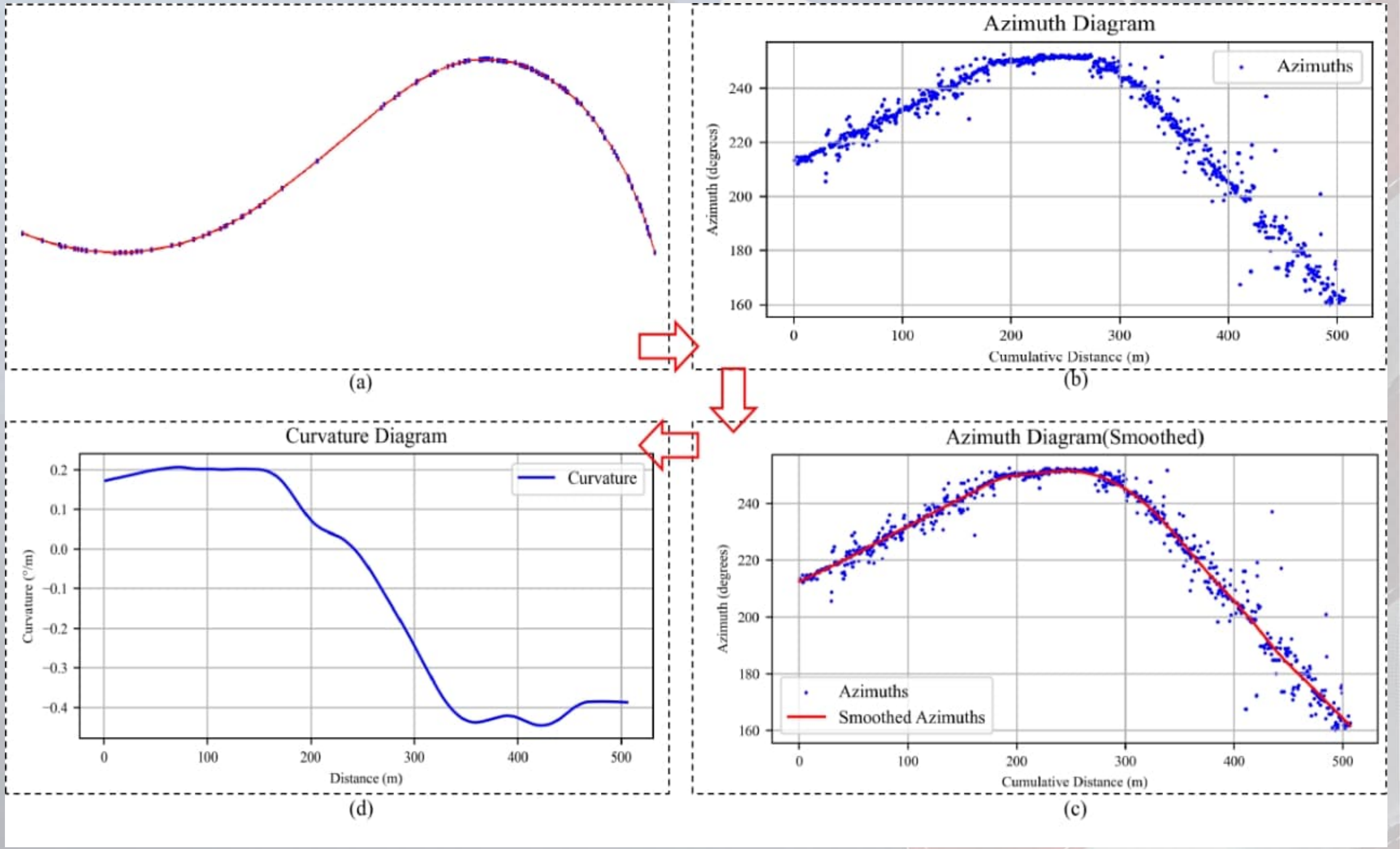
- Compute azimuth profile from road curve sequence points
- Compute curvature profile after smoothing and outlier removal
    - Azimuth: constant slope → Straight Line
    - Curvature: constant value → Circular Arc
    - Curvature: linear change → Clothoid (transition curve)
- Rule-based classifier estimates element count and locations



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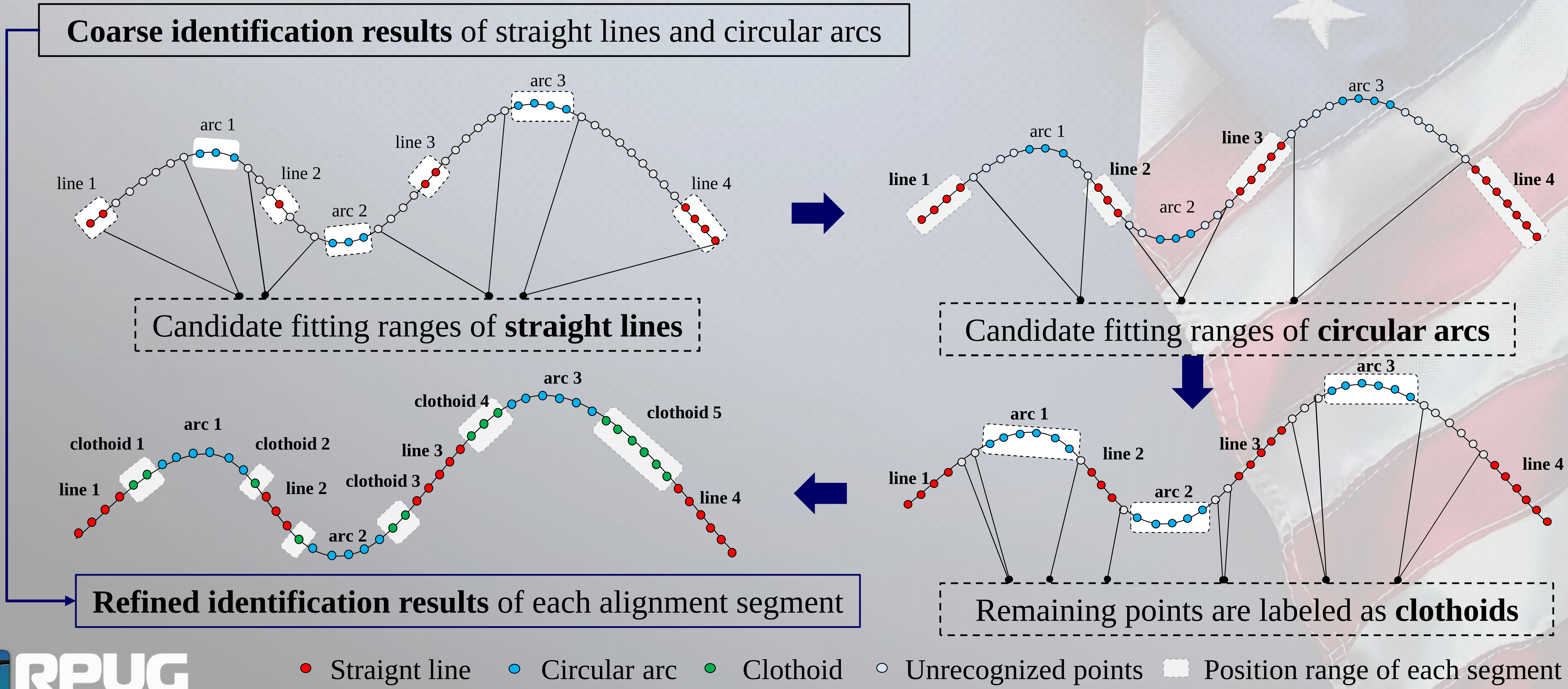
STEP3: REFINED PARAMETERIZATION

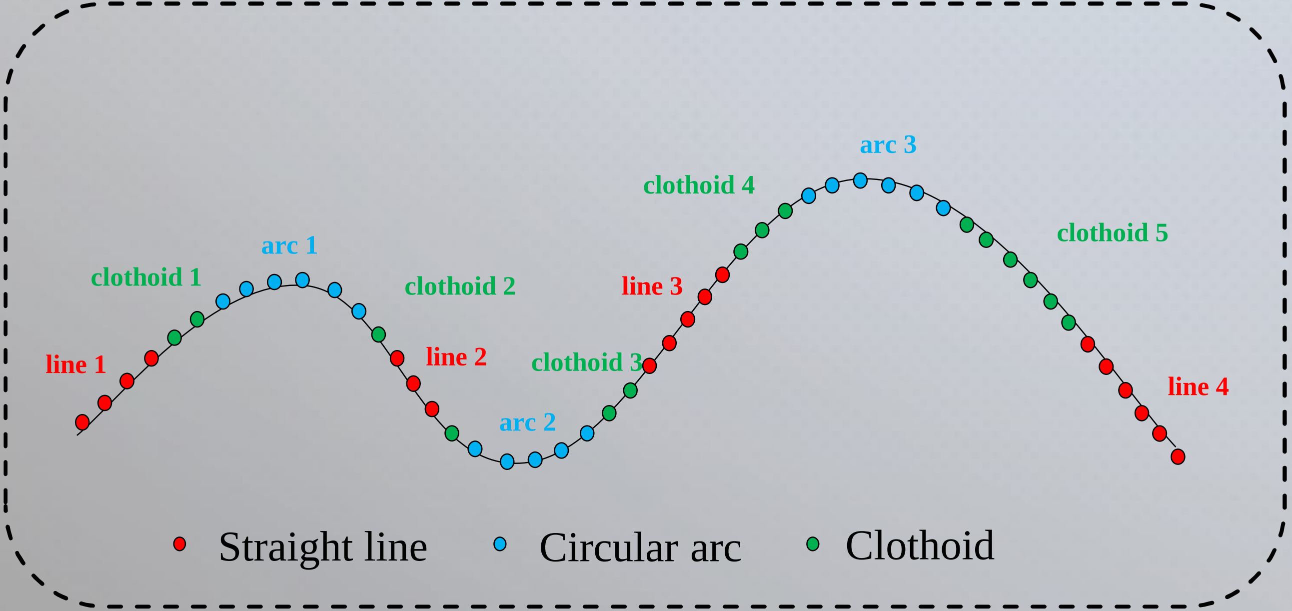
- To refine element boundaries and obtain accurate parameters, we adopt a model-fitting strategy guided by the prior geometric analysis.



STEP3: REFINED PARAMETERIZATION

- AFTER PRECISE IDENTIFICATION, ALIGNMENT PARAMETERS ARE THEN CALCULATED.

Refined identification results of each alignment segment

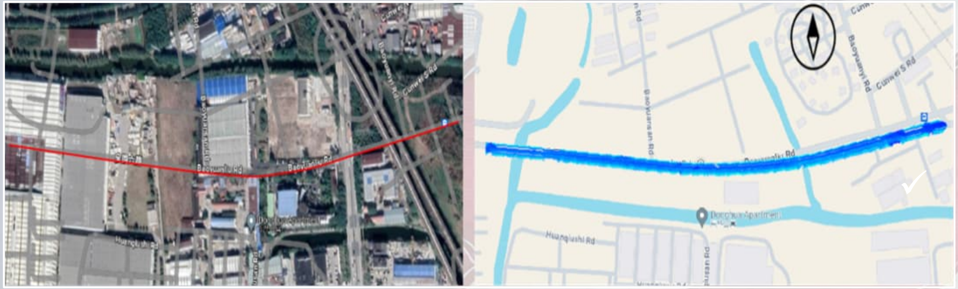


- Straight Lines:
  - Positions
  - Lengths
- Circular Arcs:
  - Positions
  - Lengths
  - Radius R_c^i:
    - ✓ R_{c1}^i from peak curvature of the diagram:
    - ✓ R_{c2}^i from arc fitting outputs.
    - ✓ the relative error < 1%, R_{c2}^i is chosen; otherwise, R_{c1}^i is used.
- Clothoids:
  - Positions
  - Lengths
  - Design parameter A_t^i:

TEST DATASET: REAL & SIMULATED ROADS

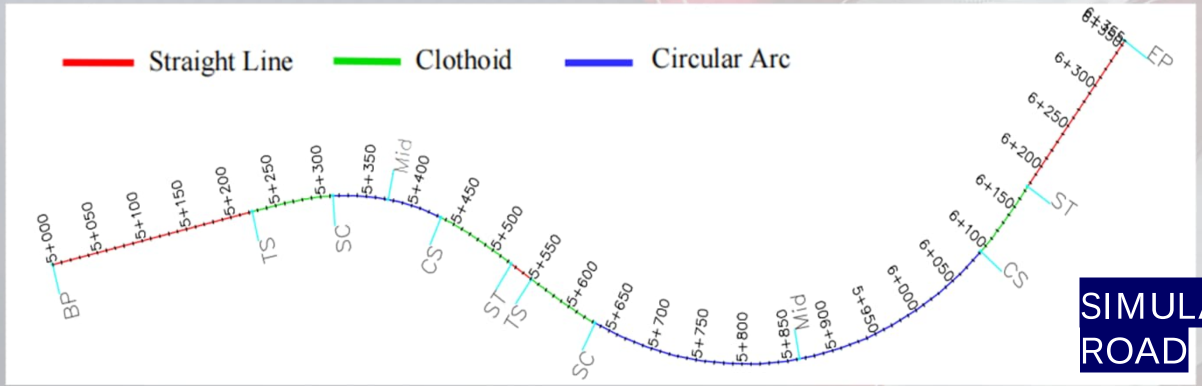
- Real-world data collected in Shanghai
- Aite Road: 1,238 m — typical circular arcs
- Baoyuan 6th Road: 851 m — extra-large-radius curve

AITE ROAD



BAOYUAN ROAD 6TH

- Simulated data: 1,355 m road in Autodesk Civil 3D
- 3 straight lines + 2 arcs + 4 clothoids (sampled at 0.5 m)
- Ground truth alignment parameters precisely controlled



SIMULATED ROAD

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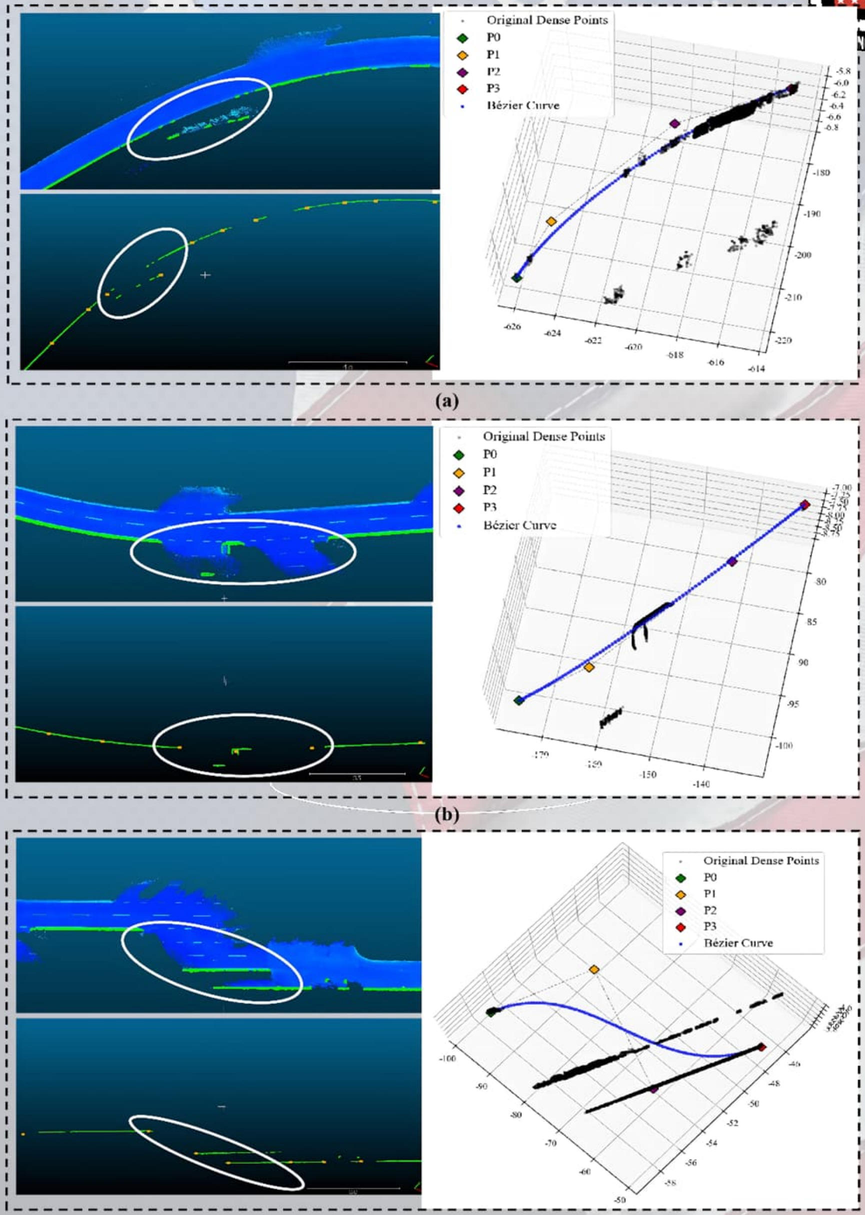
RESULTS: ROAD GEOMETRY QUALITY

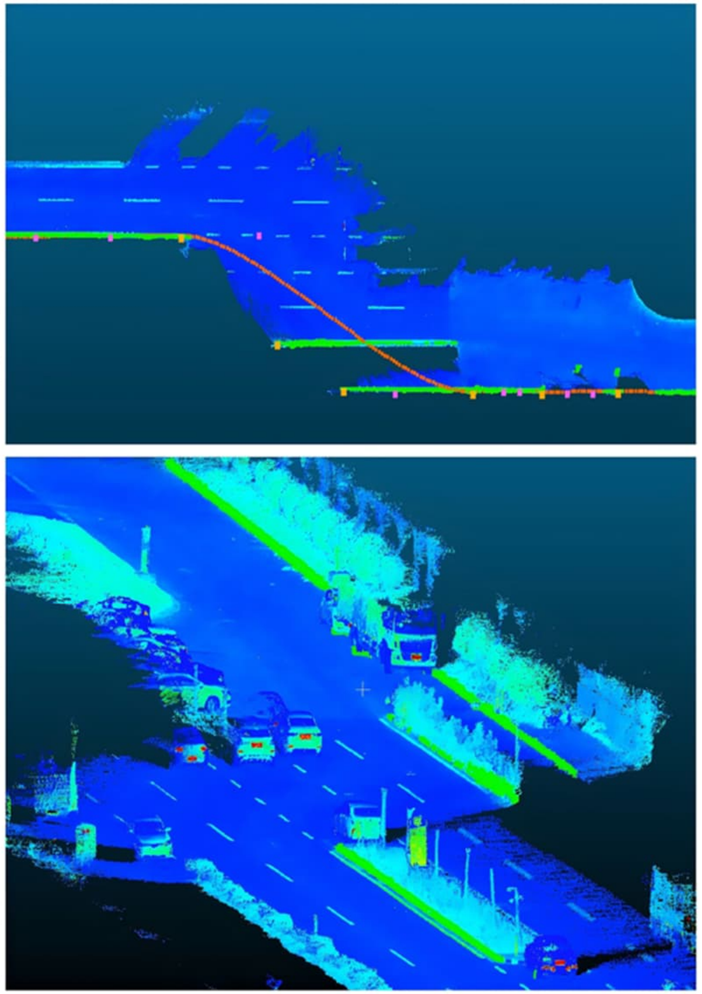
- Three challenging real-world scenarios validated:
  - (a) Dense false positives from roadside objects → correctly skipped
  - (b) Point cloud gaps → geometric continuity maintained
  - (c) Curvature-varying sections → global trend preserved
- Quantitative: 99.74% correctness, 99.41% completeness at 50 cm buffer

W_b (cm)	Correctness (%)	Completeness (%)
10	61.26	60.98
20	89.51	89.10
30	97.38	97.02
40	98.87	98.51
50	99.74	99.41



(a) (b) (c)

APPLICABILITY: LANE VARIATIONS

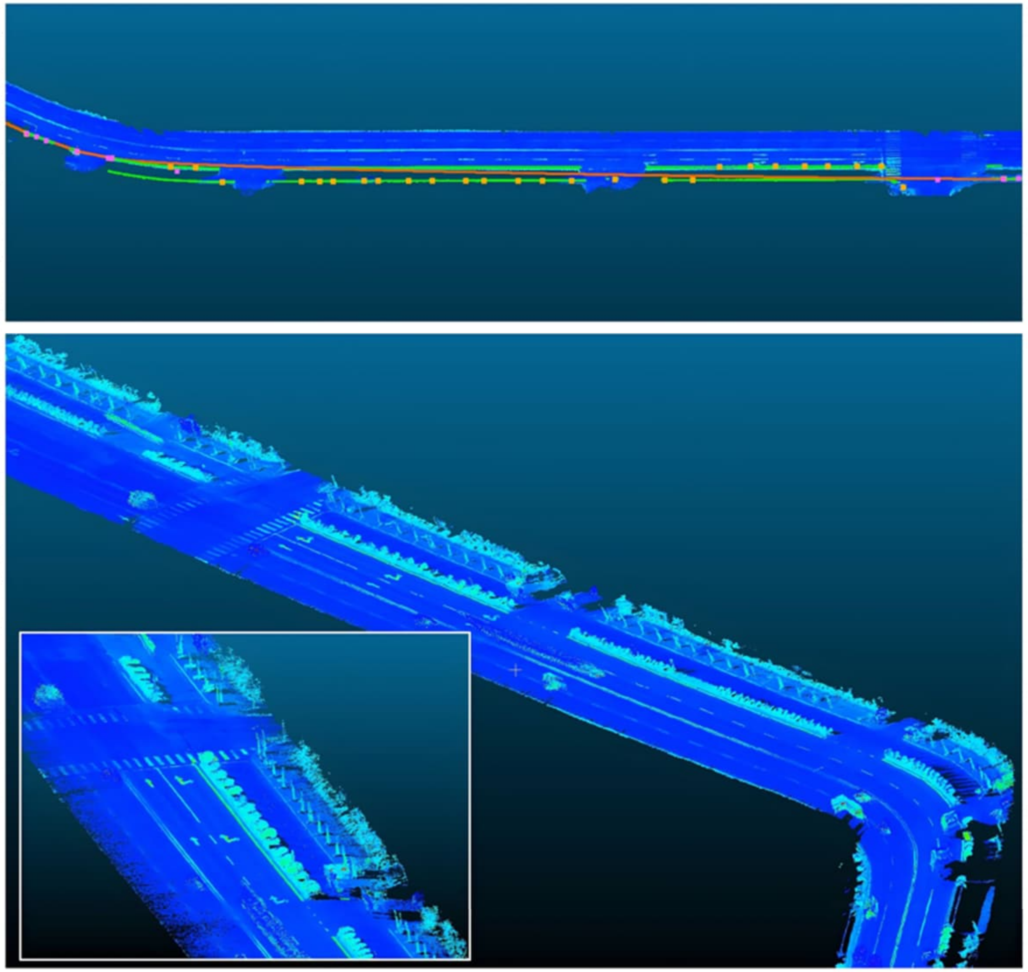


(a) Lane-widening/transition area

(A) LANE-WIDENING / TRANSITION AREA

- CURB BOUNDARY SHIFTS LATERALLY THROUGH THE TRANSITION ZONE
- SINGLE-SIDE CURB INFERENCE MAY BIAS ALIGNMENT PARAMETERS WITHIN THAT ZONE
- MITIGATION: DUAL-SIDE CURB FUSION (BOTH LEFT AND RIGHT BOUNDARIES)

APPLICABILITY: LANE VARIATIONS



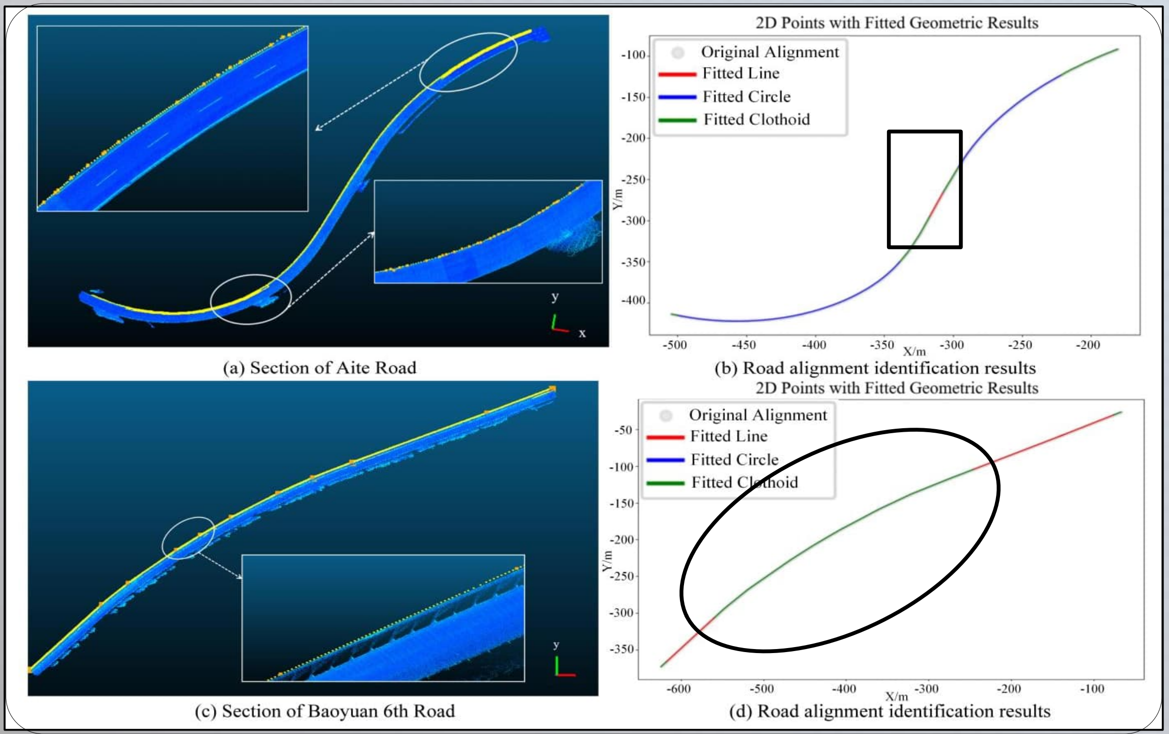
(b) Wide urban corridor with multiple curbs

(B) Wide Corridor with Multiple Curb-like Structures

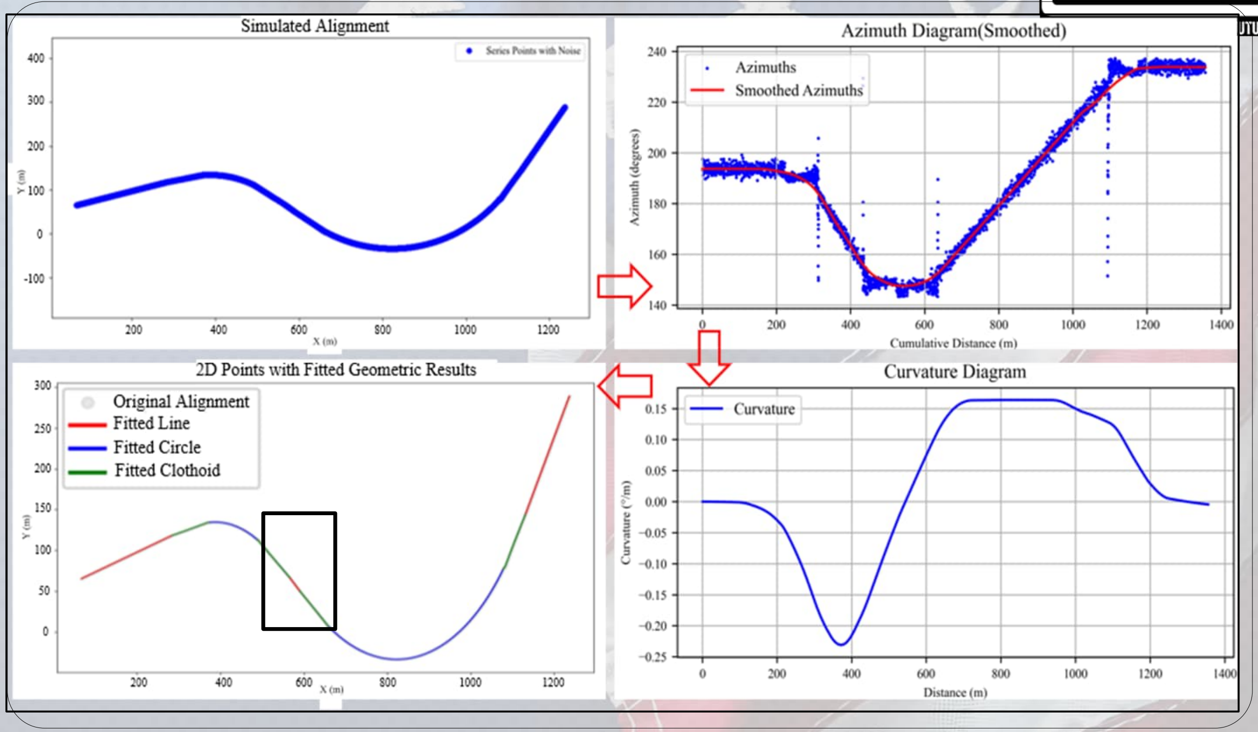
- Medians and partial coverage confuse left/right curb separation
- Result: smooth but laterally shifted boundary reference
- Mitigation: bidirectional / multi-pass scanning + stricter boundary association

Both cases define the current system boundary for single-side curb selection.

RESULTS: ALIGNMENT IDENTIFICATION



Real-world data



Simulated Data

- Both real-world and simulated roads correctly identified
  - Detects intermediate straight segments between clothoids in S-curves
  - Correctly handles extra-large-radius curves (often misidentified)
  - High precision: >97.8% precision and recall (simulated data)
  - Low numerical error for all element types (Relate Error < 3%)

RESULTS: TIME CONSUMPTION

- Time consumption experiments were conducted on a single-core CPU setting of the test machine (AMD Ryzen 9 6900HX, 3.30 GHz) with real-world data.

Stage	Real-world data		Mean Time (s/km)
	Aite Road	Baoyuan 6th Road	
Geometry Extraction	265.06 ± 8.09	247.43 ±7.56	245.32 ±7.49
Alignment Identification	30.13 ± 0.57	13.8 ± 0.26	21.03 ± 0.40

- Geometry extraction:
  - More time-intensive stage
  - Operates on dense curb point clouds
  - Encompass multiple steps
- Alignment identification:
  - Operates on a simplified and uniformly resampled curve representation
  - Importance and effectiveness of curb vectorization in accelerating downstream modeling

CONCLUSION & FUTURE WORK

What we achieved:

- Coarse-to-refined framework: first to handle lines, arcs AND clothoids from affordable MLS
- Real-world: >99% correctness and completeness at 50 cm buffer; data reduced to less than 0.5% of original size
- Simulated: 97% mean IoU for segment identification; average parameter error below 0.401%
- Runtime: 245 s/km (geometry) + 21 s/km (alignment) on single-core CPU - suitable for offline processing
- Output: standard highway-design primitives directly compatible with digital road modeling and asset management

Next steps:

- Vertical alignment extraction → full 3D road parametric model
- Collaboration with US transportation agencies for large-scale validation
- Integration with BIM and pavement management workflows

THANK YOU!

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1. Zou, Z., H. Lang*, J. Lu, and Q. Ma. Coarse-to-refined road curb segmentation from MLS point clouds. *Automation in Construction*, 2024, Vol. 166, p.105586.
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3. Chen, X., H. Lang*, Zou, Z, Chen, Y, Jiang, Y. Coarse-to-refined Road Alignment Extraction and Parameterization from MLS Point Clouds, 2026, *Automation in Construction*.